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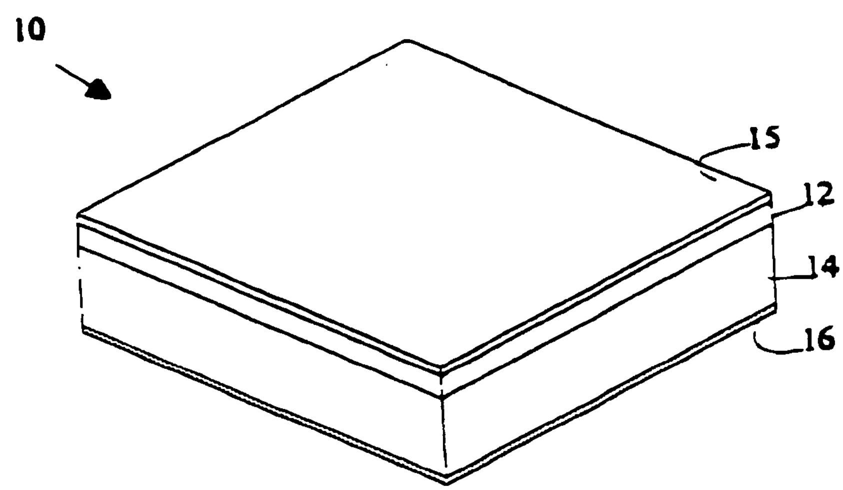
(57) Abstract

A pressure transducer (10) that converts a pressure distribution directly into a visible image. The transducer (10) may be viewed as comprising a two-layered structure sandwiched between first and second electrodes that provide a bias potential. The intermediate layers comprise a piezoresistive layer (12) and a light emitting layer (14). The piezoresistive layer (12) includes a material or structure whose resistivity varies as a function of pressure. The light emitting layer (14) is constructed from a material or structure whose light output varies in relation to the current passing through the layer.



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PIEZOLUMINESCENT SENSOR SHEET WITH A PIEZORESISTIVE LAYER

Field of the Invention

The present invention relates to sensors for measuring pressure and/or stress and more particularly, to an improved sensor that converts a pressure or stress pattern into an optical image.

Background of the Invention

Many devices for the measurement of the pressure or stress at a point or averaged over an area are known to the art. The term "stress" usually refers to a tensor quantity which may vary depending on the orientation of the surface of measurement and depending on the direction of the measurement along that surface. The term "pressure" refers to a stress that is independent of orientation. For the purposes of this discussion, the terms "stress" and "pressure" are used interchangeably.

Prior art stress sensing devices typically convert mechanical energy into electrical energy. The electrical energy is then converted into a signal which can be processed and transmitted to electronic recording devices. One method for constructing such a stress sensor utilizes piezoresistive materials. These materials respond to the application of stress with a change in their electrical resistivity. The most common types are homogeneous media, such as metals and semiconductors, and composite media. In the homogeneous media the electronic structure of the material is altered in response to the internal strains in the medium. This change in electronic structure may result in either an increase or a decrease in resistivity in response to a compressive stress. Typical examples of homogeneous piezoresistive media include metals such as ytterbium (Yb) and manganin ($Cu_{84}Mn_{12}Ni_{04}$) and semiconductors such as silicon. Composite piezoresistive media are composed of particles of a metallic or semiconducting material suspended in a (relatively) compliant insulator, as shown in Figure 1. In this case, the change in electrical resistivity of the bulk composite is the result of the decreasing separation and increasing contact between the conducting particles. As a result, such media always become more conductive upon compression. Typical examples of composite piezoresistive

media include "carbon gauges" (such as those from Dynasen Corporation, Goleta, CA) and resistive inks and adhesives (such as those from Metech, Incorporated, of Elverson, PA, or Creative Materials Incorporated of Tyngsboro, MA)

While these types of devices are adequate for single pressure measurements, they are economically unattractive when a high resolution measurement of the distribution of pressure over a surface is required. In principle, a sensor system to measure the distribution of pressure on a surface can be constructed by placing several such sensors at various locations on the surface. If only a rough measure of the variation of pressure on the surface is desired, this is a feasible approach. However, if a precise measurement of the distribution is required, this brute force approach becomes cumbersome because of the large number of individual sensors and electrical connections, and hence, there is an upper limit on size of the sensor array. In addition, the spatial resolution of such an array is limited by the dimension of the individual piezoresistive sensors.

One prior art solution to these problems is to combine many small piezoresistive sensors into a single package using methods typical for the printed circuit and integrated circuit industries. Such a system is described in U. S. Patents No. 4,734,034 (Maness *et al.*, 1988), 4,856,993 (Maness *et al.*, 1989), and 5,033,291 (Podoloff *et al.*, 1991). In these systems, the electrical connections between the sensors and the power supply and voltage measuring systems are effected by means of two sets of closely spaced metallic stripes on two substrates, arranged so that one set is at an angle to the other. The individual piezoresistive sensors are screen-printed over one or both sets of electrical leads so that an individual sensor is formed at each intersection when the two substrates are brought together. The system taught in U.S. Patent 4,856,993 uses a contact resistance composite piezoresistive of the type described by Eventoff in U. S. Patent No. 4,315,238. The other two employ a volume resistivity approach. Maness also describes multiplexing, control circuits, a regulator, an interface circuit and a computer to control the sensor. These are all made necessary by the large number of distinct electrical signals which must be kept separate so that the data can be properly interpreted.

Pressure distribution sensors of the type described by Maness are adequate to provide pressure distributions with a spatial resolution on the order of 1 millimeter. However, the number of data points becomes very large as the total area to be surveyed increases. Typically, arrays that are larger than about 50 by 50 are not practical. Furthermore, large areas cannot be observed with high spatial resolution because the number of leads to be interrogated becomes extreme.

Another disadvantage of the Maness approach to measurement of pressure distribution is the existence of voids internal to the sensor. The sensors taught by Maness require a small void at each sensor. It is necessary to provide a large number of minute passages which permit air to move in or out of these voids as portions of the sensor are compressed. This provides an added complication in the construction of the sensors.

Yet another problem with this type of sensor array is the need to provide a computer or similar device for processing the data into a usable form. The computer typically converts the individual pressure measurements into some form of graphical display or image so that an observer can better absorb the large volume of data inherent in such a pressure distribution measurement. This processing circuitry adds to the cost of the system and makes direct real time observations difficult, particularly at locations that do not easily support an online computer.

Broadly, it is the object of the present invention to provide an improved sensor system for measuring pressure distributions.

It is a further object of the present invention to provide a pressure sensor system that is less expensive than prior art sensor arrays.

It is a still further object of the present invention to provide a pressure sensor system that has higher spatial resolution than prior art sensor systems.

It is a yet further object of the present invention to provide a pressure sensing array that converts the pressure distribution to an optical image without the need to provide a computer or the like to process individual pressure measurements.

These and other objects of the present invention will become apparent to those skilled in the art from the following detailed description of the invention and the accompanying drawings.

Summary of the Invention

The present invention comprises a pressure transducer that converts a pressure distribution directly into a visible image. The transducer may be viewed as comprising a two layered structure sandwiched between first and second electrodes that provide a bias potential. The intermediate layers comprise a piezoresistive layer and a light emitting layer The piezoresistive layer includes a material whose resistivity varies as a function of pressure. The light emitting layer is constructed from a material whose light output varies in relation to the current passing through the layer.

Brief Description of the Drawings

Figure 1 is a cross-sectional view of a pressure sensing transducer according to the present invention.

Figure 2 is a cross-sectional view of a second embodiment of a pressure sensing transducer according to the present invention.

Figure 3 is a cross-sectional view of a third embodiment of a pressure sensing transducer according to the present invention.

Figure 4 is a cross-sectional view of a composite piezoresistive layer according to the present invention.

Detailed Description of the Invention

The present invention may be most easily understood with reference to Figure 1 which is a cross-sectional view of a pressure sensing sheet 10 according to the present invention. Sheet 10 may be viewed as comprising a piezoresistive layer 12 which converts variations in pressure to variations in resistivity which are then used to vary light output of a luminescent sheet 14. As will be explained in more detail below, the luminescent sheet can be constructed from any light emitting material whose light output depends on the current passing therethrough. The current is provided by maintaining a potential difference between a first continuous electrode 15 on one surface of the piezoresistive layer and a second continuous electrode 16 on the surface of luminescent sheet 14 that is not in contact with piezoresistive layer 12.

It should be noted that the present invention has superior spatial resolution compared to prior art sensor arrays. The spatial resolution of the present invention derives in part from the fact that piezoresistive layer 12 has a much lower electrical resistance through its thickness than it does between widely separated points in the plane of the sheet. In the preferred embodiment of the present invention, the piezoresistive layer is very thin, typically 0.0004 - 0.004 inches (10 - 100 μm) thick. Thus current will flow more easily across this short distance than it will flow along the plane of the material to some point which might have a lower potential. In addition, the preferred embodiment of the present invention utilizes composite piezoresistive materials which, as discussed above, are anisotropic. Because of this effect, a local decrease in resistance of the piezoresistive film will cause a local increase in the flow of current through the film and, therefore, in the emission of light. Lateral current paths, which would diffuse the image of the pressure, are less favorable for current flow because of their greater resistance.

In another embodiment, the piezoresistive layer consists of two resistive layers which are touching but not in intimate contact. As the pressure increases, the extent of the contact between the two layers increases, and hence, the resistance at the point of increased pressures decreases. Since the individual layers have high resistance to current flow parallel to the surface of each layer, the current modulation is primarily at the point of increased pressure.

The impr ved spatial resolution also derives from the fact that the entire sensor is thin. If a force is applied to a single point on the upper surface of a layer of material which rests on a elastic medium, that force is spread over a finite area at any depth into the supporting medium. The area is of the order of $A = 4\pi t^2$ where t is the thickness of the layer. For a thin piezoresistive layer on the order of micrometers to a millimeter, resistivity distributions within it can be used to discriminate stress distributions with a spatial resolution on the order of micrometers to millimeters.

If the luminescence is to be viewed from the side of the piezoluminescent sensor adjacent to the light emitting member, then electrode 16 must be of sufficient optical transparency to permit photons from light emitting layer 12 to escape. If, on the other hand, the output of the piezoluminescent sensor is to be viewed from the side with the piezoresistive member, then both electrode 14 and piezoresistive layer 12 must be transparent. Since transparent thin film electrodes are known to the art, and since the resolution would be decreased by requiring the image to be viewed through piezoresistive layer 12, the preferred embodiment of the present invention is constructed such that the image is viewed in the first configuration discussed above

For applications where the piezoluminescent sensor will not be bent or flexed, a material such as indium-tin oxide may be used to construct the transparent electrode. Indium-tin oxide may also be used if only moderate flexure is to be encountered. For a truly flexible sensor, a flexible transparent conductor such as polyaniline is preferred.

There are several types of light emitting materials which are appropriate for emission of light in a piezoluminescent sensor. Many of these have been developed or are being developed for flat panel displays. Since these are, in general, known in the art, a detailed description of their operation will not be given here. For the purposes of the present discussion, these materials may be divided into light emitting diodes (LEDs) and electroluminescent lamps, although other materials currently being developed such as surface emitting diode lasers and quantum cascade lasers (J. Faist et al., **Science** 1994) may be also be used if cost-effective sheets become available.

A light emitting diode generates light when an electrical current is carried in a semiconductor diode either by electrons or by holes. A semiconductor diode may be constructed as a layered device consisting of two or more layers, at least one of which is a hole conductor When the semiconductor diode is subjected to an appropriate bias potential, it will begin to emit light. The light output increases until it reaches a saturation current.

Semiconductor diodes based on polymer thin film materials such as poly(vinylene phenylene) are known to the art and may be used to provide LED's that emit light at various wavelengths These polymer LEDs may consist of a single layer of semiconducting material or of several layers which transport only electrons, transport only holes, or are electroluminescent (Tang and VanSlyke, J. Appl. Phys., 1987, Adachi *et al.*, Japan J. Appl. Phys., 1988a,b; Friend *et al.*, Phys. World, 1992). The polymer diodes are often produced by methods which are consistent with production of large area devices. It is also fairly easy to change the material with ligands or dopants, which allows for variations of photon energy and threshold voltage.

It should also be noted that transparent polymers which can be used as electrodes have also been reported (Gustafsson *et al.*, Nature, 1992). These newly identified materials are less brittle than the previously utilized materials, and hence, provide a means for constructing flexible LEDs.

Electroluminescent lamps consist of a phosphor layer separated from two electrodes by thin layers of dielectric material. The electrode and dielectric on at least one side must be transparent. When a high voltage alternating current (AC) is applied to the electrodes, electrons are ejected from the negative electrode and accelerated toward the positive electrode. Some of these electrons collide with the phosphor material which is thereby stimulated to emit radiation in the form of visible light. The intensity of the light depends on the amount of current flowing through the EL lamp.EL lamps are available commercially. For example, Leading Edge Industries, Inc., of Minnetonka, Minnesota sells lamps which are constructed by thick-film processes on polymer substrates. These lamps are thin (from about 0.008 inches or 0.2 millimeters) and moderately flexible.

The piezoresistive layer may be constructed utilizing pressure sensitive resistive inks which are available in a wide range of volume resistivity value including the range about $10^{-3}\,\Omega m$ to $10^{0}\,\Omega m$. The sensor must be designed with the proper combination of thickness and resistivity of the piezoresistive layer to match the electronic properties of the LED layer. If the resistance is too large there will not be enough current flowing to produce perceptible luminescence. If the resistance is too low, the change in current produced by a fractional decrease in resistance will not be great enough to cause a perceptible change in luminescence. Values of resistance between these two extremes provide the useful operating range.

In one embodiment of the present invention, the bias voltage is of an alternating current (AC) nature and of such an amplitude that luminescence is just stimulated in the LED member at the peak of the voltage but no luminescence occurs at lower voltages Thus the LED member will flash weakly and briefly at the frequency of the AC bias Application of a stress on the piezoresistive layer lowers the resistance through the layer, resulting in a larger voltage drop across the LED layer. In this new condition, the intensity and the duration of the luminescence at the peak of each bias voltage cycle is increased If the frequency of the bias voltage is high enough (about 30 Hz for human visual perception), the change will be perceived as an increase in the observed level of steady luminescence Alternatively, the piezoresistance member .may be a material such as manganin whose resistivity increases with pressure and the level of the AC bias set so that luminescence in the LED member is saturated for most of the AC bias cycle. In this case, the light level would decrease in response to a stimulus.

A sensor according to the present invention may be constructed based on an EL lamp layer as follows. The transparent electrode is deposited on a transparent substrate by sputtering, pulsed laser deposition, thermal evaporation or other suitable process. A dielectric layer with embedded phosphorescent particles is then printed on the transparent electrode by screen printing to form the light emitting layer. The piezoresistive layer can then be printed over the light emitting layer and covered with a continuous conducting layer. Optionally, an electron emitter comprising a layer of anisotropic conductor may be deposited on the light emitting layer before the application of the piezoresistive layer. This anisotropic conductor is preferably a continuous sheet of material which is intrinsically anisotropic in its electrical conductivity, such

as copper phthalocyanine or an anisotropically conducting adhesive such as 3M 9703 from 3M Corp., St. Paul. Minnesota

In another embodiment. the opaque electrode is used as the base for building the device. A thin. flexible conducting sheet such as aluminum foil or an aluminized polymer film may be used. The piezoresistive member is then deposited, preferably by screen or flexographic printing. A pattern of isolated spots may be produced by the deposition process to further enhance the spatial resolution. Finally, the LED layer is deposited over the piezoresistive member using methods such as those described in the Gustafsson *et al* reference discussed above. A vapor barrier may then be applied over the LED layer if required.

It should be noted that embodiments of the present invention that provide light output indicative of the average pressure over the sensor may also be constructed at costs significantly less than prior art pressure sensors. Refer now to Figure 2 which illustrates a sensor 20 according to the present invention that provides a pressure measurement that is indicated by the portion of the sensor that emits lights. In this case different portions of the sensor will be activated when the pressure exceeds a certain value. This device consists of continuous top and bottom electrodes 21 and 29. An electroluminescent layer 23 is connected by a resistive sheet 22 to top electrode 21. Resistive sheet 22 is composed of separate bands of different piezoresistivities 24-28. In one exemplary embodiment. band 24 requires a high pressure in order to deliver current to the portion of the electroluminescent layer 23 adjacent to it, whereas band 28 requires only a low pressure to deliver current to the portion of layer 23 adjacent to it. Bands 25-27 have intermediate and sequential sensitivities. By noting the location of the edge of the light an operator or an automatic control system can determine the pressure. A device such as that illustrated in Figure 2 can be constructed by using piezoresistive materials with the desired sensitivities.

In another embodiment of the present invention. the sensor can be used to provide a display if the pressure is greater than a predetermined value or within a predetermined range. Such a sensor is shown in Figure 3 at 30. In sensor 30, only region 33 of the area between the electroluminescent lamp layer 31 and the first electrode 32 is printed with piezoresistive ink. The remaining area, region 34, is printed with an insulating ink. When the pressure

exceeds the conduction threshold for the device, the area of the lamp layer adjacent to region 33 will generate light providing a display that matches the pattern printed in region 33. In this way, a sensor which displays the numerical value or other alpha-numeric data when the pressure exceeds predetermined value can be made in a manner similar to that described for the device of Figure 3.

If the region 34 outside of region 33 is printed with a piezoresistive ink having a threshold pressure that is greater than that of the ink used in region 33, then the message will disappear into a uniformly illuminated field when the pressure exceeds the saturation pressure of the ink in region 34. In this manner, a sensor that displays a message when the pressure is between predetermined limits may be constructed.

An embodiment of the present invention which operates as a threshold sensor rather than a continuously variable sensor can be constructed by replacing the piezoresistive layer with a composite layer as shown in Figure 4 at 50. Composite layer 50 comprises two layers 51 and 52 separated by an insulating mesh 53. At least one of the two layers must be sufficiently flexible to deform and touch the other layer when a pressure above the threshold pressure is applied. In the preferred embodiment of the present invention, both of the layers are resistive layers to reduce arcing. However, in embodiments in which arcing is not a problem, one or both of the layers may be conductors. In this case, the layer in contact with the light emitting layer may be eliminated so that pressure causes the deformable layer 51 to contact the light emitting layer directly. The insulating mesh may be constructed from a nylon mesh, non-conducting paints, or a powder of non-conducting particles.

It should be noted that if layer 51 is composed of a resistive material, then the structure shown in Figure 4 is itself a piezoresitive layer at pressures above some threshold pressure which depends on the deformation properties of layer 51 and the spacers 53. As the pressure on layer 51 increases, the area of the contact area between layer 51 and layer 52 increases. Since the resistance depends on the area of contact when a resistive material is used, the resulting structure is a piezoresitive layer as discussed above.

A piezoresitive structure can also be constructed by omitting the spacers 53 and utilizing a rough surface on either layer 51 or layer 52 to provide the spacing function. Here, it is assumed that at least one of the layers is resistive, and at least one of the layers is deformable under pressure such that the area of contact between the two layers varies with the pressure.

Various modifications to the present invention will become apparent to those skilled in the art from the foregoing description and accompanying drawings. Accordingly, the present invention is to be limited solely by the scope of the following claims.

WHAT IS CLAIMED IS:

1. A pressure transducer[10, 30] comprising: a first electrode[15] comprising a sheet of conducting material; a piezoresistive layer[12] having top and bottom sides, said top side being bonded to said first electrode[16, 29], said piezoresistive layer[12] comprising a material or structure whose resistivity varies as a function of pressure; a light emitting layer[14] having top and bottom sides, said top side being juxtaposed to said bottom side of said piezoresitive layer, said light emitting layer[14] comprising a material which emits light whose intensity depends on the magnitude of the electric current flowing through said material; and a second electrode[16] comprising a sheet of conducting material in contact with said bottom side of said light emitting layer[14].

2. The transducer[10, 30] of Claim 1 wherein said second electrode[16] is transparent to the light emitted by said light emitting layer[14].

3. The transducer[10, 30] of Claim 1 wherein said piezoresistive layer[12] comprises first and second regions[24, 25] comprising first and second materials, said first material having a different relationship between pressure and resistivity than said second material

4. The transducer[10, 30] of Claim 3 wherein said first region is spatially patterned such that said transducer[10, 30] displays a message when subjected to a pressure greater than a threshold pressure.

5. The transducer[10, 30] of Claim 1 wherein said piezoresistive layer[12] comprises first and second sub-layers[51, 52] and an insulating spacer[53], said insulating spacer[53] permitting said first and second sub-layers[51, 52] to come into electrical contact when said piezoresistive layer[12] is subjected to a pressure greater than a threshold pressure.

6. The transducer[10, 30] of Claim 5 wherein one of said first or second sub-layers[51, 52] comprises a material whose resistivity varies as a function of pressure.

7. The transducer[10, 30] of Claim 1 wherein said piezoresistive layer[12] comprises a sub-layer and an insulating spacer, said insulating spacer positioned between the said sub-layer and the light emitting layer[14], said insulating spacer permitting said sublayer to come in contact with said light emitting layer[14] when said piezoresistive layer[12] is subjected to a pressure greater than a threshold pressure.

8. The transducer[10, 30] of Claim 7 wherein said piezoresisitive layer comprises two or more regions[24-28] each having a different threshold pressure

9 The transducer[10, 30] of Claim 1 wherein said first electrode[16] and said piezoresistive layer[12] are transparent to the light emitted by said light emitting layer[14].

10. The transducer[10, 30] of Claim 1 wherein one of said layers or electrodes[33] is spatially patterned to display a message when said transducer[10, 30] is subjected to a pressure in a predetermined pressure range.

WO 97/16834 PCT/US96/17205

FIGURE 1

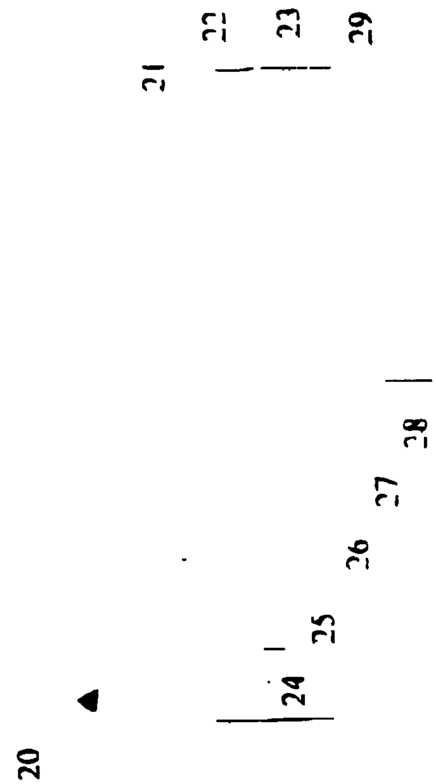

FIGURE 2

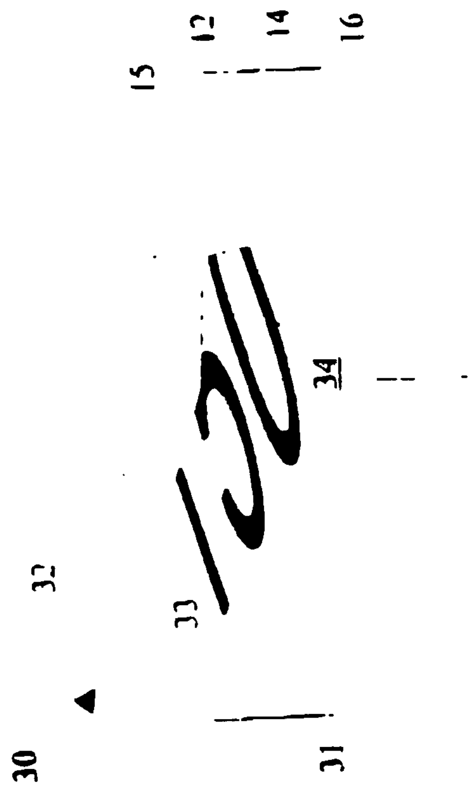

FIGURE 3

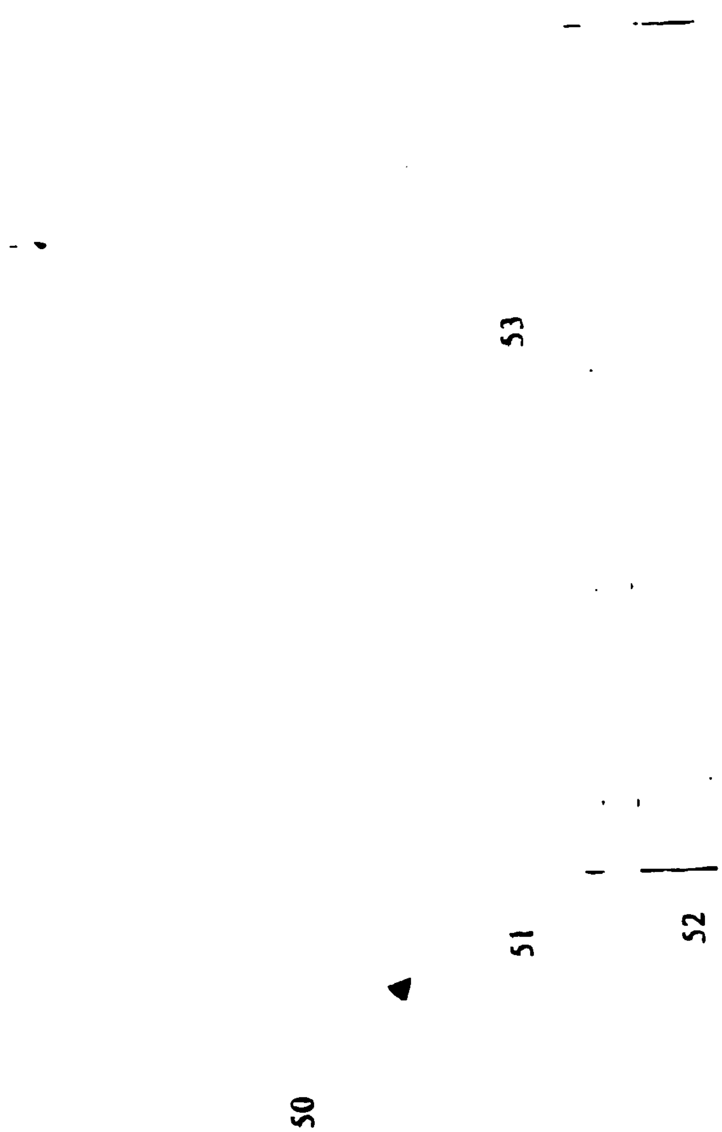

FIGURE 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/US96/17205

A. CLASSIFICATION F SUBJECT MATTER

IPC(6) H01C 10/10
US CL 338/47
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U S 310/311, 338 339, 338/13, 43 4747

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 4,878,107 A (HOPPER) 31 October 1989, see col. 7, lines 6-53.	1,2,4,9,10
Y	US 3,154,720 A (COOPERMAN) 27 October 1964, see Figs. 5 and 6	1,2,4,9,10
Y	US 3,065,378 A (ZAKS) 20 November 1962, see entire document.	1,2,4,9,10
Y	US 2,816,236 (ROSEN) 10 December 1957, see entire document.	1,2,4,9,10

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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